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# Modelling public health benefits of various emission control options to reduce NO<sub>2</sub> concentrations in Guangzhou

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Supplementary material for this article is available [online](#)

## Abstract

The local government of the megacity of Guangzhou, China, has established an annual average NO<sub>2</sub> concentration target of 40  $\mu\text{g m}^{-3}$  to achieve by 2020. However, the *Guangzhou Ambient Air Quality Compliance Plan* does not specify what constitutes compliance with this target. We investigated a range of ambition levels for emissions reductions required to meet different possible interpretations of compliance using a hybrid dispersion and land-use regression model approach. We found that to reduce average annual-mean NO<sub>2</sub> concentration across all current monitoring sites to below 40  $\mu\text{g m}^{-3}$  (i.e. a compliance assessment approach that does not use modelling) would require emissions reductions from all source sectors within Guangzhou of 60%, whilst to attain 40  $\mu\text{g m}^{-3}$  everywhere in Guangzhou (based on model results) would require all-source emissions reduction of 90%. Reducing emissions only from the traffic sector would not achieve either interpretation of the target. We calculated the impacts of the emissions reductions on NO<sub>2</sub>-attributable premature mortality to illustrate that policy assessment based only on assessment against a fixed concentration target does not account for the full public health improvements attained. Our approach and findings are relevant for NO<sub>2</sub> air pollution control policy making in other megacities.

## 1. Introduction

In response to rapidly increasing levels of air pollution, governments at all levels in China have implemented a range of laws, policies, and plans. For example, in 2014 China's National People's Congress (NPC) Standing Committee passed a new Environmental Protection Law (Zhang *et al* 2016a), and in 2018 amended the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution (Ministry of Ecology and Environment of the People's Republic of China 2018). As a result of the efforts being put into curbing emissions by both national and local governments, substantial improvements in Chinese air quality have been reported in recent years (Li *et al* 2015, Zhang *et al* 2016b, Huang *et al* 2018, Liu *et al* 2018, UN Environment 2019), although other researchers have argued that despite increased political focus on the issues, further measures are needed for more profound improvement (Kostka 2016, Shi *et al* 2019).

Guangzhou is an example of many cities in China that do not currently meet the Chinese air quality standards (GB 3095-2012) (Ministry of Ecology and Environment 2012). Consequently, as required under both the Chinese national laws cited above the Guangzhou Municipal People's Government has developed the Guangzhou Ambient Air Quality Compliance Plan (2016–2025) (People's Government of Guangzhou Municipality 2017). Of the six Chinese priority air pollutants (SO<sub>2</sub>, NO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, CO and O<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>) is of particular concern at the urban and sub-urban scale. Exposure to ambient concentrations of NO<sub>2</sub> is associated with premature mortality and other public health burdens (WHO 2013, Faustini *et al* 2014, Crouse *et al* 2015). The Chinese air quality standard for NO<sub>2</sub> is currently set equal to the World Health

Organization (WHO) air quality guideline, at  $40 \mu\text{g m}^{-3}$  as an annual average, and the Guangzhou aspiration is to achieve this by 2020 (and also to achieve an annual average  $\text{NO}_2$  concentration of  $38 \mu\text{g m}^{-3}$  by 2025) (People's Government of Guangzhou Municipality 2017).

$\text{NO}_2$  derives primarily from  $\text{NO}_x$  ( $\text{NO}$  and  $\text{NO}_2$ ) emitted from road transport, domestic, commercial and industrial combustion, and shipping (MEIC 2016, Fu *et al* 2017, Liu *et al* 2017, Ding *et al* 2018). Due to the ubiquitous nature of combustion sources and the relatively short lifetime of  $\text{NO}_2$ , its concentrations are highly spatially variable (Beirle *et al* 2011, Cyrus *et al* 2012, Gurung *et al* 2017). However, although the Guangzhou Ambient Air Quality Compliance Plan states that the  $\text{NO}_2$  target needs to be met in all areas in Guangzhou, it is not defined how compliance is to be evaluated, for instance whether this includes at locations without monitoring stations. Furthermore, because the ultimate aim of setting an  $\text{NO}_2$  concentration target is to alleviate the negative impacts on health, the estimation of potential city-wide population health gains from policy interventions that target  $\text{NO}_2$  emission reductions from local sources also requires highly spatially resolved  $\text{NO}_2$  concentration data.

Estimation of  $\text{NO}_2$  at non-monitored locations requires some form of modelling. However, modelling  $\text{NO}_2$  (and other pollutant) concentrations at high spatial resolution for Chinese cities such as Guangzhou presents a considerable challenge, both because of the geographical scale of the domain (for example, Guangzhou has an area  $>7000 \text{ km}^2$ ), and the relative paucity of data needed as inputs to models (He *et al* 2018). The two main approaches to urban-scale air pollution modelling are dispersion models that endeavour to explicitly simulate physical-chemical processes at urban scale (Visscher 2013), and land-use regression (LUR) models that are based on empirical spatial statistics (Briggs *et al* 1997, Jerrett *et al* 2005). Applications of either approach in China have so far been limited by the city size and data availability (He *et al* 2018).

We recently developed and demonstrated a hybrid modelling approach that addresses some of the limitations of applying a dispersion or land-use regression model in isolation (He *et al* 2019). In our hybrid approach, a dispersion model is used to derive  $\text{NO}_2$  concentrations at a set of 'virtual' receptor locations—strategically chosen to represent geographical areas, the expected  $\text{NO}_2$  concentration range and population weighting—which are then used as input to generate an LUR model to map annual-average  $\text{NO}_2$  concentrations across the entire domain. An advantage of this method is that it is possible to derive spatially-explicit maps of  $\text{NO}_2$  concentrations for the whole domain under alternative future emissions scenarios that are underpinned by process-based dispersion simulations.

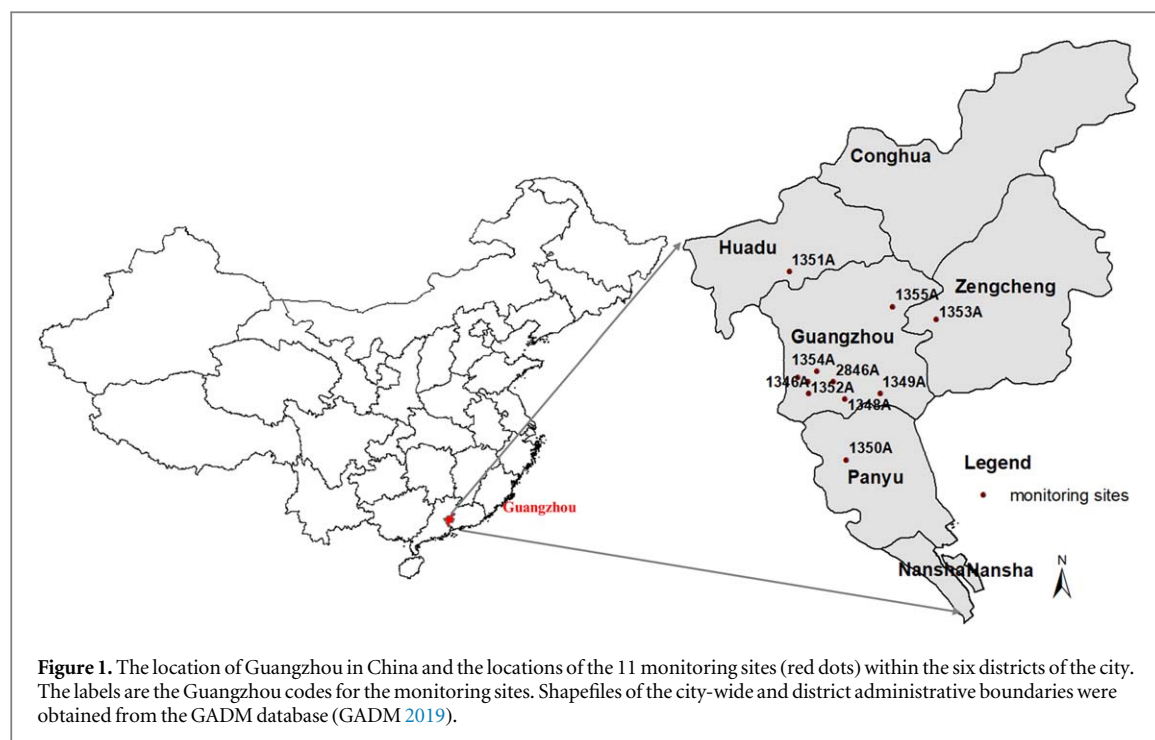
The aim of the current study is two-fold. First, we apply our modelling approach (He *et al* 2019) to investigate the ability of a range of example emission reduction scenarios to meet the Guangzhou Ambient Air Quality Compliance Plan target of  $40 \mu\text{g m}^{-3}$  annual-average  $\text{NO}_2$  concentration. Since it is not clear what constitutes compliance with the target, we present results that illustrate the emissions reductions required for modelled concentrations to meet the following interpretations of a  $40 \mu\text{g m}^{-3}$  target:

- Target Interpretation 1: the average of the annual average concentrations at all current  $\text{NO}_2$  monitoring sites meets the target (TI1).
- Target Interpretation 2: the annual average concentration at all current  $\text{NO}_2$  monitoring sites meet the target (TI2).
- Target Interpretation 3: the population-weighted annual average concentration in Guangzhou meets the target (TI3).
- Target Interpretation 4: the annual average concentration everywhere in Guangzhou meets the target (TI4).

Secondly, we use our modelled  $\text{NO}_2$  concentrations to determine the changes in population exposure to  $\text{NO}_2$ , and the associated population premature mortality avoided. We use these data to illustrate that the use of a concentration threshold as a policy metric can fail to convey to policy-makers and the public the extent of population health gain achieved across a range of potential emissions reductions even where reductions fail to deliver the concentration target (and the continuing public health gain for reductions that go beyond meeting the concentration target).

Our study does not set out to simulate real-world proposed policy measures, but to illustrate an approach to identifying the scale of the mitigation challenge to achieve city-wide concentration standards set under existing policy targets and what their associated potential health gains may be. Economic costs and benefits are not evaluated.

Whilst the results are based on consistent model results for the specific situation in Guangzhou, they provide relevant evidence to decision makers designing effective air pollution control policies in other fast-growing megacities in China and elsewhere globally.



## 2. Method

### 2.1. A hybrid modelling approach

The city of Guangzhou (population 14 million) is located on the north side of the Pearl River Delta (figure 1) and comprises six districts in a total area of 7434 km<sup>2</sup>. As described by He *et al* (2019), the size of the city and lack of some data limit the application of domain-wide air pollution dispersion modelling. Similarly, the eleven monitoring sites that measure NO<sub>2</sub> concentrations are too few to develop spatially representative NO<sub>2</sub> concentrations using a LUR approach. To overcome these challenges we developed a hybrid model, described by He *et al* (2019), which uses a combination of both dispersion and LUR modelling. The ADMS-Urban dispersion model v4.1 (CERC 2017) is used to derive NO<sub>2</sub> concentrations at 83 receptor locations across Guangzhou systematically selected to represent the anticipated concentration range (from background to roadside) in each of the six districts, with additional location weighting according to population density (since the overall focus is estimation of population NO<sub>2</sub> exposure). The NO<sub>2</sub> concentrations at these selected receptors locations are then used to develop a LUR model for NO<sub>2</sub> concentrations across the whole city domain. The LUR model is built with the 84 potential predictor variables listed in supplementary information (SI) table S1 available online at [stacks.iop.org/ERC/2/065006/mmedia](https://stacks.iop.org/ERC/2/065006/mmedia). The final LUR model variables and the evaluation statistics for the LUR model for 2017 ('base case') NO<sub>2</sub> concentrations, as reported previously in He *et al* (2019), are summarised in SI tables S2 and S3, respectively. The spatial resolution of the final modelled NO<sub>2</sub> concentrations is 25 m.

We use the same method here to develop spatial maps of NO<sub>2</sub> concentration for each of the emissions reductions scenarios described in the following section. The use of the dispersion model means that NO<sub>2</sub> concentrations at the set of 83 receptor locations for different emissions reductions scenarios are derived from a process-based model. The variables selected for the subsequent LUR models for the different scenarios are listed in SI table S4. Because road length was used as a proxy of traffic, and therefore cannot reflect the proportion change of traffic emission, the final model might underestimate the impacts of traffic emission reduction.

The ADMS-Urban model was also used to derive NO<sub>2</sub> concentrations at each of the 11 NO<sub>2</sub> monitor locations in order to address target interpretations TI1 and TI2 of compliance with a Guangzhou NO<sub>2</sub> target.

### 2.2. Modelling scenarios

To explore the scale of emissions reductions required to meet the Guangzhou NO<sub>2</sub> concentration target of 40 µg m<sup>-3</sup>, the following different scenarios were simulated using ADMS-Urban to derive concentrations at the 83 pre-selected receptor locations.

- (1) Base case: 2017 emissions

- (2) Scenarios A<sub>x</sub>: reductions of NO<sub>x</sub> and VOCs emission in all source sectors equally by 10% decrements (x) between 10% and 90%
- (3) Scenarios B<sub>x</sub>: reductions of NO<sub>x</sub> and VOCs emission in the road transport sector by 10% decrements (x) between 10% and 90%

Road traffic NO<sub>x</sub> emissions comprise 21.3% of all NO<sub>x</sub> emissions (including shipping) in the model domain for Guangzhou (MEIC 2016) but transport is the dominant (i.e. comprises >45%) land-based NO<sub>x</sub> emission source in the majority of the individual grid cells (SI figures S1 and S2 and table S5). Changes in road traffic emissions only were explicitly modelled in ADMS-Urban (CERC 2017), so the B<sub>x</sub> scenarios were undertaken to demonstrate the change of NO<sub>2</sub> concentration if interventions focusing only on reductions of NO<sub>x</sub> and VOCs emissions from road traffic were to be implemented.

Under the base case scenario (2017), the total annual NO<sub>x</sub> and VOCs emissions are 180.2 kt and 357.3 kt, respectively (SI table S6). When comparing outcomes from the two sets of scenarios it is important to note that emissions reductions are substantially larger under the A<sub>x</sub> scenarios than the B<sub>x</sub> scenarios. For example, in scenario B<sub>90</sub>, the 90% reductions in emissions from road transport result in reductions of about 34 kt NO<sub>x</sub> and 45 kt VOC. In scenario A<sub>90</sub>, the 90% reductions in emissions across all sectors corresponds to reductions in NO<sub>x</sub> and VOC of 162 kt and 322 kt respectively (SI table S6).

We included emissions reductions in VOC as well as NO<sub>x</sub> in the model simulations since VOC are the other class of primary emissions that can impact on the gas-phase NO<sub>x</sub> chemistry. The same percentage reductions in VOC and NO<sub>x</sub> were applied, although equal reductions of each is probably not a realistic outcome of particular policy measures. However, the VOC reductions imposed in the model scenarios in fact impact relatively little on the results of our study which investigates the impacts of emissions reductions in the Guangzhou domain on intraurban levels of NO<sub>2</sub> in the Guangzhou domain. We demonstrate this by conducting a sensitivity simulation with the dispersion model of NO<sub>2</sub> concentrations at the 11 monitoring sites in Guangzhou for a scenario with 50% reduction in NO<sub>x</sub> emissions but baseline VOC emissions. The results from this simulation are compared in SI figure S3 with those for the simulation with baseline NO<sub>x</sub> and VOC emissions and for the scenario where both NO<sub>x</sub> and VOC emissions are reduced by 50%. Figure S3 shows that the inclusion or not of 50% VOC emissions reductions alongside the 50% reductions in NO<sub>x</sub> emissions has very little impact on the NO<sub>2</sub> concentrations at these locations (across a range of absolute NO<sub>2</sub> concentrations) compared with the change in NO<sub>2</sub> concentrations brought about by the reductions in NO<sub>x</sub> emissions. The average change (increase) in NO<sub>2</sub> concentration for the scenario with 50% NO<sub>x</sub> emissions reduction and no VOC reductions compared with the scenario where both VOC and NO<sub>x</sub> emissions are reduced by 50% is only 1.1 μg m<sup>-3</sup>, which equates to only a 2.5% change in the mean of the NO<sub>2</sub> concentrations across the 11 sites under these scenarios (43 μg m<sup>-3</sup>). In comparison, the 50% reduction in the NO<sub>x</sub> emissions causes an average change across the 11 sites of more than 18 μg m<sup>-3</sup>.

Meteorological variability can have a significant influence on air quality by affecting the advection, diffusion and deposition of air pollutants, although less so for annual average concentrations compared with shorter averaging times. The magnitude of inter-annual meteorological variability on annual average NO<sub>2</sub> in Guangzhou was explored by also running the dispersion model for the 11 monitoring sites using the Guangzhou meteorology for each of the years 2013 to 2016. Emissions were maintained at the 2017 base case year. The ranges in the annual averages of the meteorological variables input into the dispersion model across these five years are shown in SI table S7.

### 2.3. Health burden calculation

Total premature deaths attributable to the simulated concentrations of NO<sub>2</sub> across the whole Guangzhou domain under each scenario were calculated as described by Walton *et al* (2015), using the association with all-cause premature mortality of 2.45% (95% CI: 2.34%, 2.58%) per 10 μg m<sup>-3</sup> NO<sub>2</sub> from Zhang *et al* (2011). The association is taken to be linear across the NO<sub>2</sub> concentration range here. The number of deaths in 2017 in Guangzhou was 60 900 (Guangzhou Municipal Public Security Bureau 2016). Population density data at 100 m × 100 m (for the year 2015) was obtained from WorldPop (WorldPop 2019). The population-weighted average concentration ( $E$ ) for NO<sub>2</sub> across the whole of Guangzhou was calculated as follows,

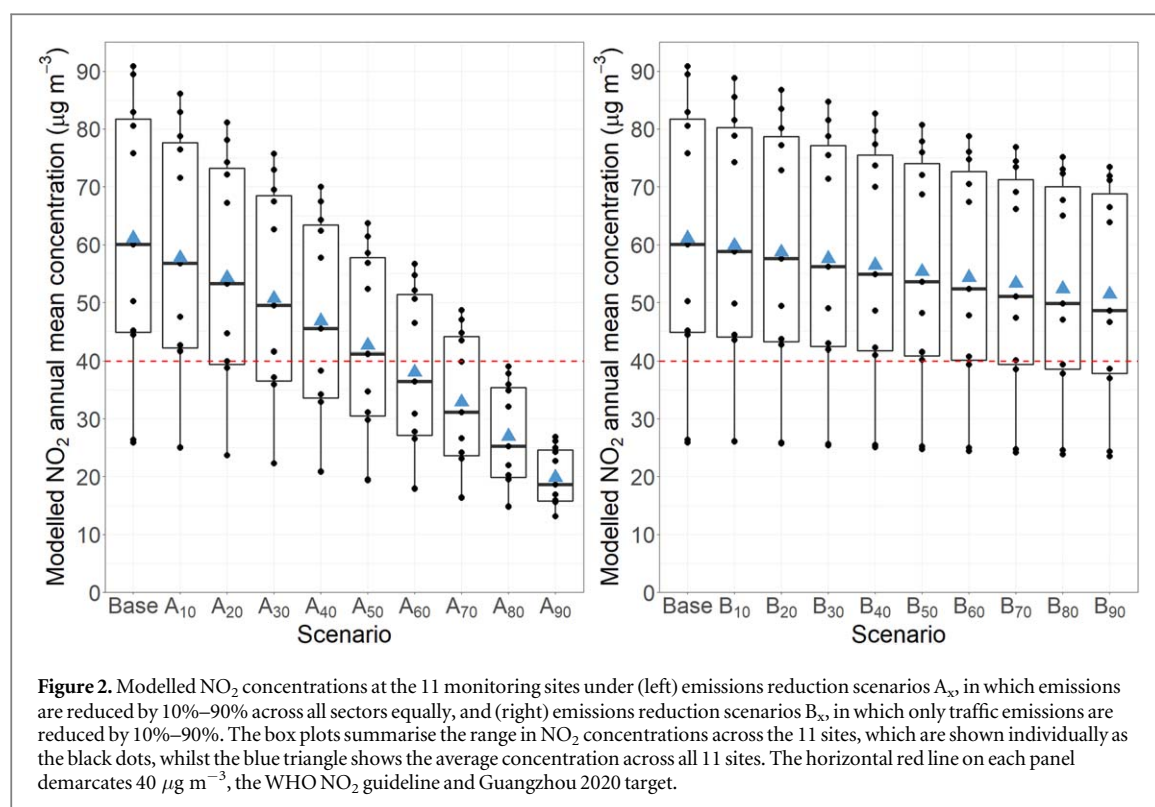
$$E = \frac{1}{Pop} \sum_i C_i Pop_i \quad (1)$$

where  $C_i$  and  $Pop_i$  are the concentration and the number of people in each cell  $i$  of the concentration map.

The attributable deaths from exposure to ambient NO<sub>2</sub> in Guangzhou was calculated by multiplying the attributable fraction (AF) by number of all-cause deaths (equations (2)–(4)), where RR refers to relative risk.

$$RR = 1.0245^{(E/10)} \quad (2)$$





$$AF = (RR - 1) / RR \quad (3)$$

$$\text{Attributable death} = \text{the number of deaths} \times AF \quad (4)$$

In common with studies of this kind, population data at residential address was used. An assessment of the impact of work location on population level of exposure requires additional information on population distributions at different times (Reis *et al* 2018).

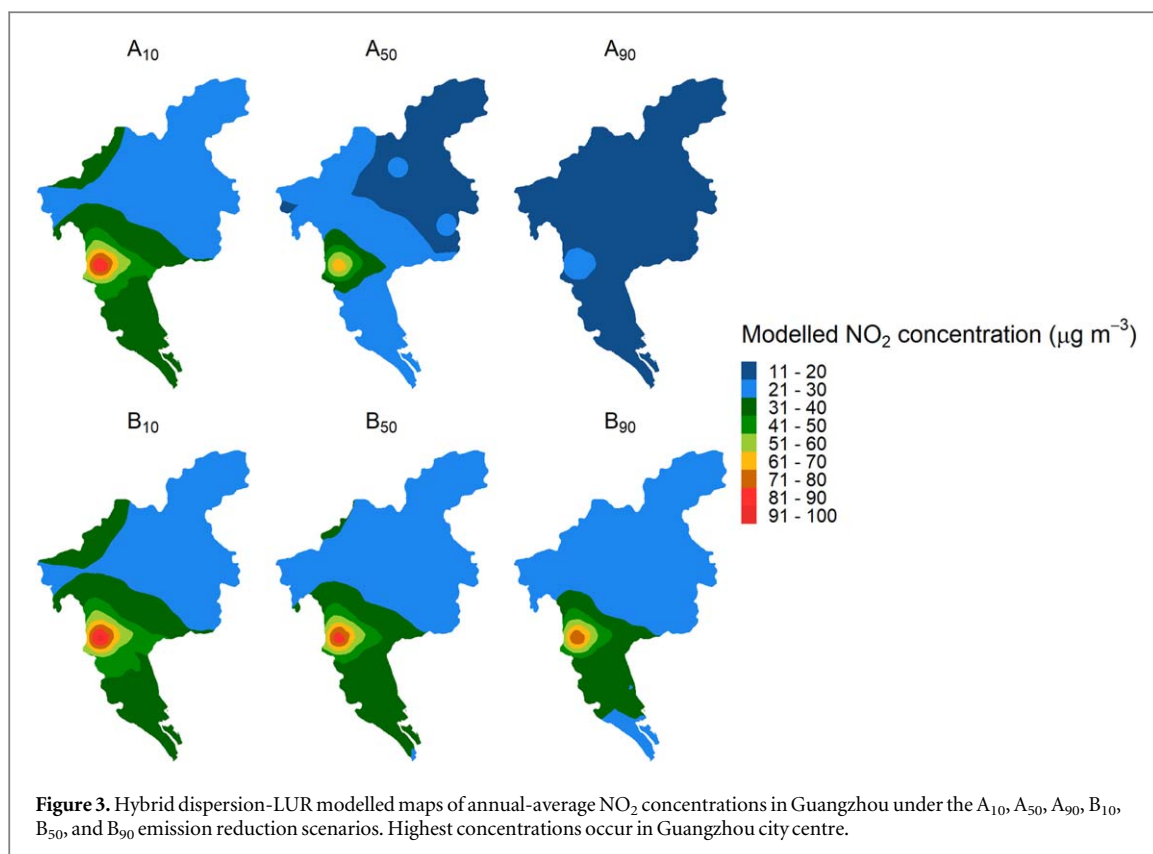
### 3. Results

#### 3.1. Modelled NO<sub>2</sub> concentration changes at monitoring sites

The Guangzhou Ambient Air Quality Compliance Plan does not specify whether modelling is to be used for compliance assessment. Without modelling, compliance can only be evaluated using the monitor data. The NO<sub>2</sub> concentrations simulated using the ADMS-Urban dispersion model at the 11 monitoring sites for the base case and the 18 emissions reduction scenarios are summarized in figure 2. For comparison, the NO<sub>2</sub> concentrations simulated at the 11 monitor sites for the base case for the five meteorological years tested are shown in SI figure S4. The latter figure shows that NO<sub>2</sub> concentrations at a given receptor varied relatively little for the different meteorological scenarios (at most a few µg m<sup>-3</sup>) compared with the changes associated with the emissions reduction scenarios shown in figure 2.

As expected, concentrations at monitoring sites under A<sub>x</sub> scenarios are lower than those under B<sub>x</sub> scenarios because absolute emissions reductions are larger when applied to all sectors than when applied only to road transport (figure 2). It is notable that the range in NO<sub>2</sub> concentrations across the 11 sites gets smaller as emissions reductions become greater. Concentrations at sites with the highest concentrations, which are located nearer to main roads, fall off faster than at sites with the lowest concentrations, which are background sites. This is because NO<sub>2</sub> concentrations are strongly influenced by local NO<sub>x</sub> emission sources, so locations closer to strong sources, particularly roads, are more immediately impacted by reductions in emissions from those sources. This effect is greater for the A<sub>x</sub> emissions reduction scenarios (figure 2) since these also include reductions in domestic and other local NO<sub>x</sub> sources, not just traffic sources. As a consequence of the relatively greater effect of emissions reductions on higher concentration locations, there is a smaller reduction in the average NO<sub>2</sub> concentrations for the scenarios with smaller reductions in emissions (toward the left side of each panel in figure 2) compared with the reductions in the average NO<sub>2</sub> concentration when emissions reductions are already substantial (toward the right side of each panel in figure 2).

Figure 2 suggests that to attain an average annual-average NO<sub>2</sub> concentration across all monitoring sites of 40 µg m<sup>-3</sup> (TII) would require a 60% reduction of emissions in all sectors (A<sub>60</sub>). (We note here that since our



emissions reductions scenarios go in 10% increments it is more strictly accurate to state that TI1 would be reached with a scenario somewhere between A<sub>50</sub> and A<sub>60</sub>, and likewise for other statements below referring to emissions reductions required to meet certain target interpretations.) To attain 40  $\mu\text{g m}^{-3}$  or less at all 11 monitoring sites individually (TI2) would require an 80% reduction from all emitting sectors (A<sub>80</sub>). Figure 2 further suggests that neither of the Target Interpretations 1 or 2 are attainable if interventions aiming at emission reductions only from road transport are implemented.

### 3.2. Spatial assessment of NO<sub>2</sub> concentration changes

The data presented in section 3.1 show modelled concentrations of NO<sub>2</sub> under emissions reductions scenarios only for the 11 locations in Guangzhou that currently have NO<sub>2</sub> monitoring, yet compliance with the Guangzhou NO<sub>2</sub> target may be required at non-monitor locations. Furthermore, 11 monitoring locations in a city the size of Guangzhou cannot capture the full extent of variation in population exposure to NO<sub>2</sub>. Our hybrid dispersion-LUR model maps of the spatial variation in NO<sub>2</sub> concentration across Guangzhou for six examples of the 18 emissions reductions scenarios are shown in figure 3. For all scenarios, concentrations of NO<sub>2</sub> remain highest in the city centre where most people live and lowest in the north of the city domain. Figure 4 illustrates the spatial patterns in change in NO<sub>2</sub> concentration against the base-case scenario for the same emissions reduction scenarios presented in figure 3. As the finer spatial structure of the changes in NO<sub>2</sub> concentration cannot be visualised in figure 4, figure 5 shows a magnification of the changes in NO<sub>2</sub> concentration in the city centre for the A<sub>50</sub> and B<sub>50</sub> scenarios (using a different colour scale compared with figure 4).

The A<sub>x</sub> scenarios show more substantive reductions in annual average concentrations of NO<sub>2</sub> (figures 3 and 4) than the B<sub>x</sub> scenarios, given the larger absolute emissions reductions applied in the former set. In terms of the spatial variation, the modelled annual average NO<sub>2</sub> concentrations under the A<sub>90</sub> scenario ranged from 13.0 to 27.8  $\mu\text{g m}^{-3}$  while under the B<sub>90</sub> scenario they ranged from 20.0 to 78.4  $\mu\text{g m}^{-3}$  (figure 3). In the base case they ranged from 21.5 to 99.7  $\mu\text{g m}^{-3}$  (He *et al* 2019). Figure 5 illustrates the substantial spatial structure to the changes in NO<sub>2</sub> concentration that is difficult to discern in the maps of figure 4 that present the changes for the entire Guangzhou city area. The NO<sub>2</sub> reductions are greatest near roads in both A and B scenarios but figure 5 illustrates that the A scenarios also lead to larger reductions in NO<sub>2</sub> away from roads than the B scenarios. Nevertheless, these simulations suggest that only the most stringent emissions reduction scenario simulated (A<sub>90</sub>) would result in NO<sub>2</sub> concentrations of less than 40  $\mu\text{g m}^{-3}$  in all locations, including in the city centre, i.e. would meet Target Interpretation TI4. This target interpretation would not be achieved even with complete elimination of road traffic emissions, without reductions in other sources as well.



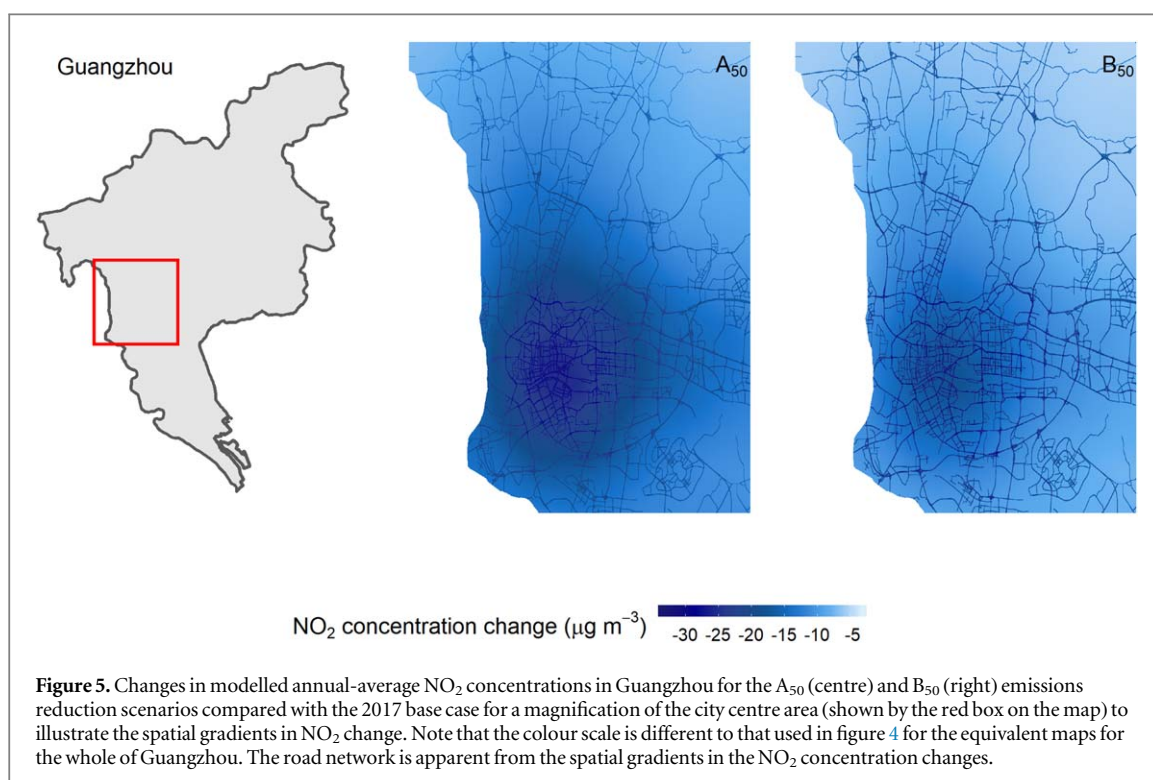
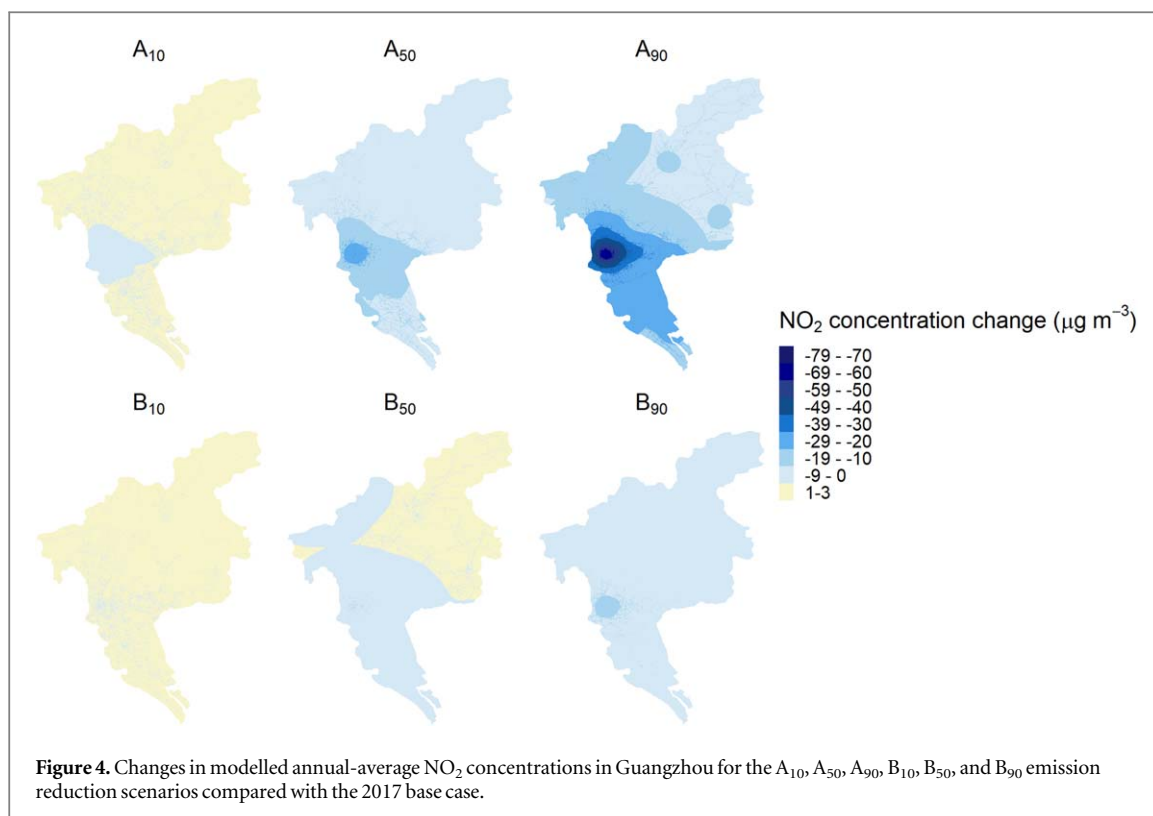


Figure 4 shows that under small and moderate emissions reductions the annual average  $\text{NO}_2$  concentration are simulated to increase slightly in some areas of Guangzhou. This is most apparent for the B<sub>10</sub> scenario, under which the maximum simulated increase in  $\text{NO}_2$  concentration is  $2.59 \mu\text{g m}^{-3}$ . There are two explanations for the small increases in  $\text{NO}_2$  when emissions are reduced. First, it reflects errors in simulated  $\text{NO}_2$  concentration inherent in the two different LUR models being subtracted; when the effect of emissions reductions in an area are small the subtraction of surfaces of roughly similar concentration can lead to a positive value. These positive values of a couple of  $\mu\text{g m}^{-3}$  provide an indication of model surface uncertainty. There is also potentially an

**Table 1.** Summary for selected emissions reduction scenarios of population-weighted annual-average NO<sub>2</sub> concentration, the percentage of people living at locations with annual average NO<sub>2</sub> concentration >40  $\mu\text{g m}^{-3}$ , the number of NO<sub>2</sub>-attributable premature deaths, and the number of NO<sub>2</sub>-attributable lives saved compared with the base case. The ranges given for the numbers of attributable premature deaths reflect the confidence interval given for the health response coefficient used in the calculation. The data for all emissions reductions scenarios is given in SI table S8.

Scenario	Population-weighted NO <sub>2</sub> concentration ( $\mu\text{g m}^{-3}$ )	Proportion of population at locations with NO <sub>2</sub> concentration >40 $\mu\text{g m}^{-3}$ (%)	Number of NO <sub>2</sub> -attributable premature deaths	Reduction in number of NO <sub>2</sub> -attributable premature deaths cf base case
Base	52.5	60.0	7270 [6960–7620]	n.a.
<i>Emission reductions—all sources</i>				
A <sub>10</sub>	49.9	58.6	6932 [6642, 7273]	338 [318, 347]
A <sub>50</sub>	36.8	37.8	5195 [4974, 5454]	2075 [1986, 2165]
A <sub>90</sub>	18.0	0	2594 [2481, 2727]	4676 [4479, 4893]
<i>Emission reductions—traffic sources only</i>				
B <sub>10</sub>	51.7	63.4	7167 [6868, 7519]	103 [92, 101]
B <sub>50</sub>	47.5	53.5	6615 [6337, 6941]	655 [623, 679]
B <sub>90</sub>	43.5	48.6	6087 [5831, 6389]	1183 [1129, 1231]

atmospheric chemistry contribution. Where NO<sub>x</sub> emissions are large, the concentrations of O<sub>3</sub> are low, and rate of oxidation of NO emissions to NO<sub>2</sub> is suppressed; therefore as the NO<sub>x</sub> emissions are initially lowered more O<sub>3</sub> is available to convert NO to NO<sub>2</sub>. The effect is proportionally greater where NO<sub>2</sub> concentrations are lower.

### 3.3. Modelled potential health gains of different emission changes

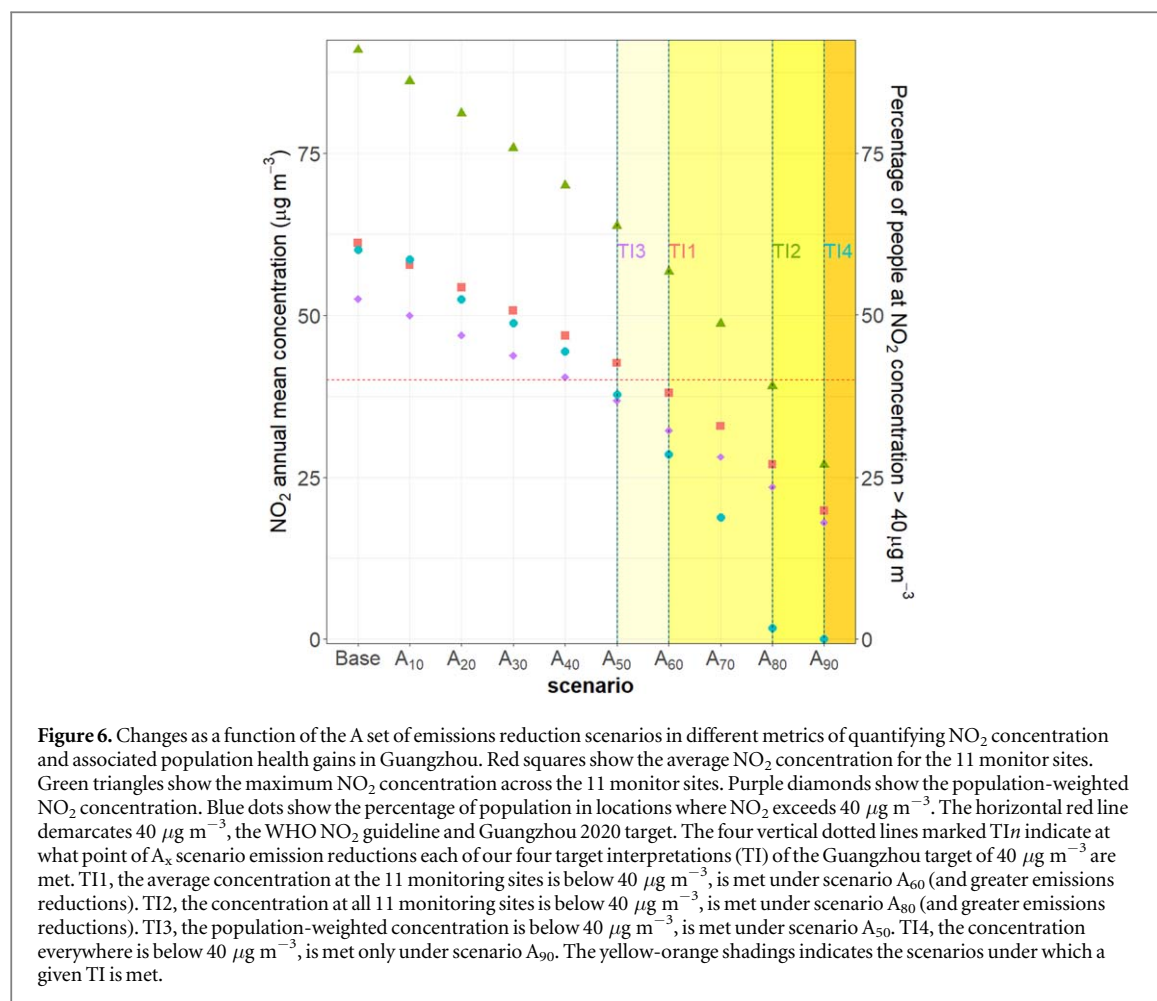
Table 1 presents, for each scenario, the population-weighted NO<sub>2</sub> concentration, the percentage of the Guangzhou population living at locations where NO<sub>2</sub> concentration exceeds 40  $\mu\text{g m}^{-3}$ , the estimated number of NO<sub>2</sub>-attributable premature deaths, and the number of NO<sub>2</sub>-attributable premature deaths avoided compared with the base case. (Calculations of premature deaths are subject to uncertainty in the health response coefficient as well as that in simulated NO<sub>2</sub> concentrations.) Under A<sub>x</sub> scenarios, the number of premature deaths avoided is almost three times that of the equivalent percentage emissions reductions under B<sub>x</sub> scenarios, which is due to the greater absolute emission reductions in A<sub>x</sub> scenarios than in B<sub>x</sub> scenarios. Under the A<sub>x</sub> scenarios, no part of the population is exposed to concentrations exceeding 40  $\mu\text{g m}^{-3}$  when the emissions reductions reach 90% (table 1). Under the B<sub>x</sub> scenarios, even for the B<sub>90</sub> scenario nearly half (48.6%) of the population resides in locations where modelled NO<sub>2</sub> concentrations still exceed 40  $\mu\text{g m}^{-3}$ . The corresponding population-weighted NO<sub>2</sub> concentration for A<sub>90</sub> and B<sub>90</sub> emissions reduction scenarios are 18.0  $\mu\text{g m}^{-3}$  and 43.5  $\mu\text{g m}^{-3}$  respectively. However, although the population-weighted NO<sub>2</sub> concentration for the A<sub>90</sub> emissions reduction scenario is less than 40  $\mu\text{g m}^{-3}$ , the modelled number of NO<sub>2</sub>-attributable premature deaths under A<sub>90</sub> is still 2594 [2481, 2727].

## 4. Discussion

### 4.1. Interpretation of NO<sub>2</sub> policy targets

We have found that different interpretations of the Guangzhou Municipal People's Government's target to attain an NO<sub>2</sub> concentration of 40  $\mu\text{g m}^{-3}$  can lead to different amounts of emissions reduction required. These are illustrated in figure 6.

If modelling is not used, then compliance can only be assessed via the concentrations measured at the 11 sites in Guangzhou that monitor levels of NO<sub>2</sub> (our target interpretations TI1 and TI2). Our simulations suggest that the scenario in which NO<sub>x</sub> emissions from all source sectors are reduced by 80% (the A<sub>80</sub> scenario) would achieve the goal of reducing NO<sub>2</sub> concentrations at all monitor sites to  $\leq 40 \mu\text{g m}^{-3}$  (TI2). The slightly smaller reductions in emissions required to reach this interpretation of the target, compared with the A<sub>90</sub> scenario that is required to satisfy the interpretation that NO<sub>2</sub> concentrations must not exceed 40  $\mu\text{g m}^{-3}$  everywhere (TI4), and which can only be evaluated through modelling, is because there are no monitors at the 'hotspots' simulated in the spatial model to have the highest concentrations. If an interpretation of the target is that the average NO<sub>2</sub> concentration across the 11 monitor sites is to be  $\leq 40 \mu\text{g m}^{-3}$  (TI1), then this is met with the A<sub>60</sub> scenario. A population-weighted concentration of  $\leq 40 \mu\text{g m}^{-3}$  (TI3) is met under scenario A<sub>50</sub>, but this scenario still leaves 37.8% of the Guangzhou population living in locations where NO<sub>2</sub> concentration exceeds 40  $\mu\text{g m}^{-3}$  (table 1 and figure 6).



Our simulations illustrate the substantial challenge to reduce NO<sub>2</sub> concentrations to 40 µg m<sup>-3</sup>, whatever way compliance with this target may be assessed, via actions on emissions sources in Guangzhou alone. Although NO<sub>2</sub> concentrations reduce more rapidly with emissions reductions at locations where the concentrations are high initially, because these are the locations closest to local emissions of NO<sub>x</sub> (e.g. heavily trafficked roads), huge efforts are still required to reduce these ‘hotspot’ concentrations to ≤40 µg m<sup>-3</sup>. These hotspots also tend to be the places where most people live. None of the scenarios reducing emission from road traffic sector alone (the B<sub>x</sub> scenarios) can achieve any of the four interpretations of the 40 µg m<sup>-3</sup> target (table 1). Thus only substantial overall emissions reductions across all sectors will be viable to make progress towards attaining the limit values. In fact, our simulations show that only a scenario in which NO<sub>x</sub> emissions from all source sectors are reduced by 90% (the A<sub>90</sub> scenario) results in annual average NO<sub>2</sub> concentrations ≤40 µg m<sup>-3</sup> everywhere in Guangzhou. As noted already, the difference in response between all-sector emissions reductions and transport-only emissions reduction reflects the different absolute reductions in NO<sub>x</sub> (and VOC) between these two sets of scenarios. Also, a proportion of the NO<sub>2</sub> concentrations in these simulations is due to import of NO<sub>2</sub> from outside the Guangzhou domain, which is not impacted by emissions reductions applied within the domain. Figures 2 and 3 indicate that even with almost total Guangzhou emissions reductions there is simulated to be ~12 µg m<sup>-3</sup> NO<sub>2</sub> at locations in the domain most remote from NO<sub>x</sub> sources. We also note again a limitation in our LUR modelling arising from lack of traffic intensity data on specific road links.

Specific interventions targeted at very high concentration areas (for example, a city centre) may be a more practical approach to avoid such locations dominating the overall attainment of limit values. Whilst applying a given percentage emission reduction within a city centre zone would not reduce the NO<sub>2</sub> concentration in the city centre more than applying that emission reduction domain wide, such targeted reductions may well be more economically and technically efficient in terms of absolute ‘unit’ of NO<sub>2</sub> metric gained per absolute reduction in NO<sub>2</sub> emissions. The actual mitigation scenario(s) followed in practice needs to strike a balance between the amount of emissions reductions needed in an area of given size, whilst also taking account of other essential factors such as cost, technical practicality and societal acceptance. Designing and modelling all such aspects of emissions reductions is challenging. Overall behavioural change (Vardoulakis *et al* 2018) and measures

attenuating negative health impacts (Lucock *et al* 2017, Stevens *et al* 2019) should also be explored alongside traditional policy interventions aiming to reduce NO<sub>2</sub> concentration levels.

#### 4.2. Utility of NO<sub>2</sub> concentration threshold as a policy target

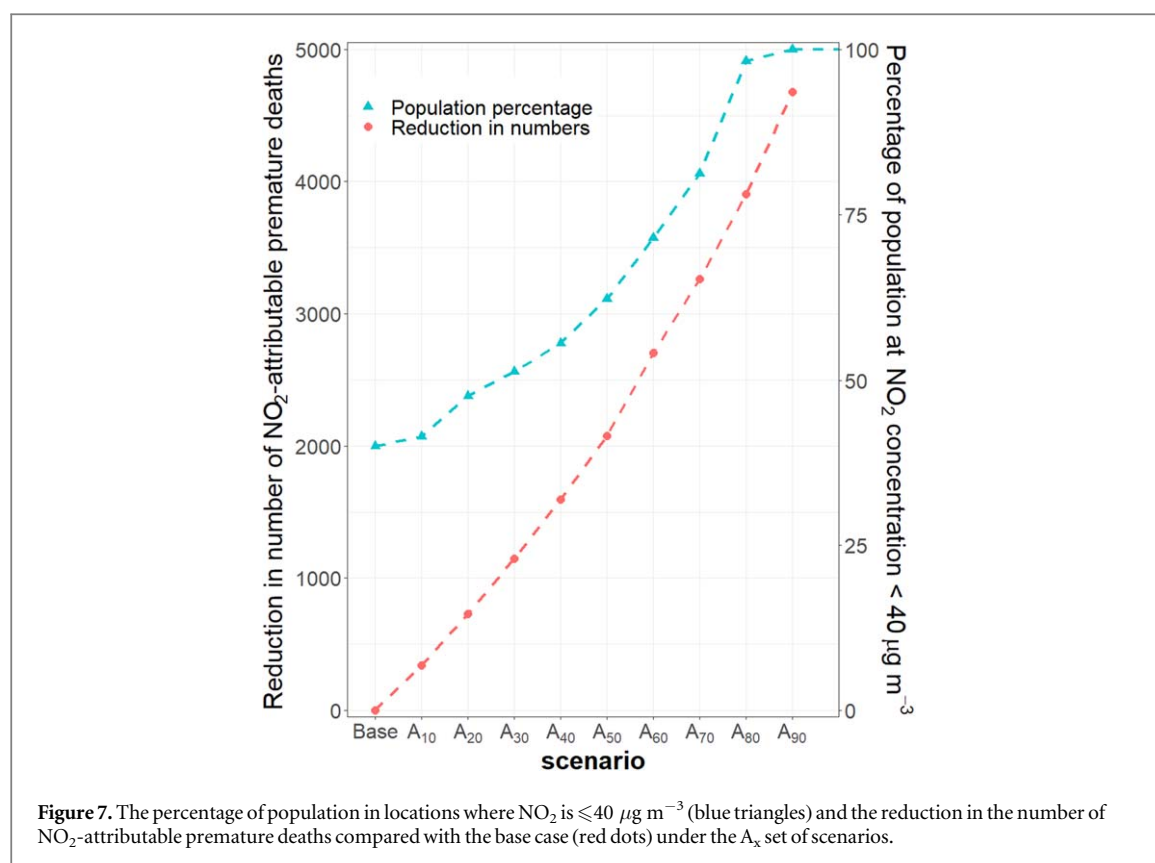
Given the scale of the emissions reductions required that are illustrated by our model simulations, one could argue that a 40  $\mu\text{g m}^{-3}$  objective for NO<sub>2</sub> concentration over a megacity is unattainable through actions in that city alone, as long as internal combustion engines and combustion in stationary sources are the predominant source of NO<sub>x</sub> emissions in cities. For example, since the 1980s, the UK government has committed to reducing NO<sub>2</sub> concentration; but despite the continuous improvement, in many larger cities in the UK it is still a challenge to meet the current limit value for annual average NO<sub>2</sub> concentrations of 40  $\mu\text{g m}^{-3}$  (Carnell *et al* 2019). The same is true for many cities across other European countries (Fuller 2018).

On the other hand it is important to remember that NO<sub>2</sub> concentration targets within cities are driven by the desire to improve adverse health outcomes associated with NO<sub>2</sub>, and in this context using a specific concentration target to assess progress towards improvement in air quality can underplay the actual extent of gains made in improving population health outcome. For example, it is important to note that, even for our ‘softer’ interpretations of attainment of the Guangzhou target (TI1 and TI3), substantial reductions in the number of NO<sub>2</sub>-attributable premature deaths compared to the base case are anticipated: 2703 [2589, 2824] for TI1 and 2075 [1986, 2165] for TI3. These represent reductions in attributable mortality of 37% and 29%, respectively, relative to the 7270 NO<sub>2</sub>-attributable deaths associated with the base case (in comparison, the reductions in NO<sub>2</sub>-attributable premature deaths for TI2 and TI4 are 3905 [3741, 4084] and 4676 [4479, 4893] respectively), but with substantially less stringent emissions reductions than needed to attain TI2 or TI4.

The use of a concentration threshold as a policy target to deliver health protection against NO<sub>2</sub> has further shortcoming in that the 40  $\mu\text{g m}^{-3}$  concentration does not constitute a no-effect threshold for NO<sub>2</sub>, and in fact current epidemiological evidence is that there is no zero-effect threshold for exposure to NO<sub>2</sub> (Beelen *et al* 2014, COMEAP 2018). In other words, there are health gains if concentrations go down in locations irrespective of whether the concentrations are above or below the target value. Therefore what is fundamentally relevant in relation to potential policy measures is not the change in proportion of locations with NO<sub>2</sub> concentrations  $\leq 40 \mu\text{g m}^{-3}$ , nor the change in the numbers of people in locations with NO<sub>2</sub> concentrations  $\leq 40 \mu\text{g m}^{-3}$ , but by how much the cumulative population exposure changes. Quantification of the latter shows that there are greater rates of population health gain as emissions are reduced than is implied by considering only the rates of change of number of people with NO<sub>2</sub> exposure brought below 40  $\mu\text{g m}^{-3}$ . This point is clearly illustrated in figure 7 for our Guangzhou example emissions reduction scenarios. The gradient of the plot of the number of NO<sub>2</sub>-attributable deaths saved (compared to base case) for the set of A emissions reduction scenarios is steeper than the plot of the percentage of population at locations with NO<sub>2</sub>  $\leq 40 \mu\text{g m}^{-3}$ . The message is particularly obvious for the smallest emissions reduction scenario simulated (the A<sub>10</sub> scenario), which makes almost no difference to the number of people in locations with concentrations  $\leq 40 \mu\text{g m}^{-3}$  compared with the base case (and which might therefore be deemed to be having no effect), but yet delivers health gains of 338 attributable deaths avoided. The need to consider cumulative population health exposure rather than progress against a concentration target is again graphically apparent in figure 7 at the other end of the scale of emissions reductions: further emissions reductions beyond the A<sub>90</sub> scenario will not lead to more people living at locations with NO<sub>2</sub> concentration  $\leq 40 \mu\text{g m}^{-3}$ , since 100% of the population would then already do so, but further emissions reductions would continue to deliver additional NO<sub>2</sub>-attributable deaths avoided.

The use of attainment of a specific concentration as a policy target actually has the potential to promote a detrimental effect on policy ambition levels (Fuller and Font 2019), since there might be a perception that once a 40  $\mu\text{g m}^{-3}$  is reached that is ‘job done’; or worse, to encourage the perception that it doesn’t matter if previously low concentrations are allowed to increase as long as they still remain below 40  $\mu\text{g m}^{-3}$ . This may lead to situations where compliance may be achieved, but more pronounced public health impacts could be attained at lower cost, or irrespective of individual locations being in exceedance. The data we present for our example modelling in Guangzhou illustrate the quantitative evidence on population health gain for different scenarios (as opposed to evidence just on NO<sub>2</sub> concentrations) that needs to be fed into policy decisions related to costs and benefits associated with attaining a concentration target in any large city.

The reduction scenarios investigated here only represent reductions in emissions within the Guangzhou city domain. Emissions reductions in the region surrounding Guangzhou will contribute to lowering background NO<sub>2</sub> concentrations coming into Guangzhou, which would likely enable the city to attain air quality limit values for NO<sub>2</sub> with less additional emissions reductions within Guangzhou itself than simulated here. In addition, emissions reductions within Guangzhou will have the additional benefit of lowering NO<sub>2</sub> concentrations, with consequent gains in health, in areas surrounding and downwind of Guangzhou, in addition to the health gains calculated here for Guangzhou alone. As studies in both Europe and China have pointed out, joint emissions



controls within both the target area and surrounding areas are most effective for improving air quality holistically (Reis *et al* 2012, Xue *et al* 2014, Ou *et al* 2016, Yu *et al* 2019).

The benefits of emissions reductions in Guangzhou calculated as reductions in NO<sub>2</sub>-attributable premature death presented in this paper also represent only part of the overall benefits. Emission reductions have important additional health and environmental benefits other than those directly experienced through NO<sub>2</sub> on health. For instance, NO<sub>x</sub> emission reductions will also contribute to reducing the formation of secondary inorganic aerosols and hence PM<sub>2.5</sub> concentrations, and also reduce dry and wet deposition of reactive nitrogen on terrestrial ecosystems (Gao *et al* 2015, Guo *et al* 2018, Zhu *et al* 2018, Kanakidou 2019, Qiao *et al* 2019). Measures to reduce NO<sub>x</sub> emissions will also often lead to reductions in co-emitted pollutants such as primary particulate matter and black carbon. Therefore, instead of focusing on attaining regulatory concentration targets only, a focus on rate of change and accounting for the integrated benefits from emission reduction might be more appropriate. This paper only focuses on NO<sub>2</sub>, but benefits from emission reduction need to be assessed along with other pollutants including PM<sub>2.5</sub> and O<sub>3</sub>.

## 5. Conclusions

To overcome limitations on availability of data for urban air quality modelling, we used a hybrid dispersion and land-use regression model to explore the impact of emission reductions within Guangzhou on annual-average NO<sub>2</sub> concentrations in relation to a policy target of  $40 \mu\text{g m}^{-3}$ . We found that reductions from traffic emissions alone will not achieve the target everywhere but that substantial reductions in all-sector emissions will be required. On the other hand, we found that emissions reductions lead to faster gain in NO<sub>2</sub>-attributable premature mortality avoided than in geographical area achieving the concentration target, and therefore recommend that a health-based metric of air quality be considered in parallel.

Whilst the results of the model simulations we present are for the specific situation in Guangzhou, the methodology we use and our discussion in relation to limitations of an NO<sub>2</sub> concentration target for assessing effectiveness of air pollutant emissions policies, are relevant to decision makers in other fast-growing megacities in China and elsewhere globally.



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## References

- Beelen R et al 2014 Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project *The Lancet* **383** 785–95
- Beirle S, Boersma K F, Platt U, Lawrence M G and Wagner T 2011 Megacity emissions and lifetimes of nitrogen oxides probed from space *Science* **333** 1737–9
- Briggs D J, Collins S, Elliott P, Fischer P, Kingham S, Lebreton E, Pryl K, Van Reeuwijk H, Smallbone K and Van Der Veen A 1997 Mapping urban air pollution using GIS: a regression-based approach *Int. J. Geogr. Inf. Sci.* **11** 699–718
- Carnell E, Vieno M, Vardoulakis S, Beck R, Heaviside C, Tomlinson S, Dragosits U, Heal M R and Reis S 2019 Modelling public health improvements as a result of air pollution control policies in the UK over four decades—1970 to 2010 *Environ. Res. Lett.* **14** 074001
- CERC 2017 ADMS-Urban User Guide [WWW Document]. URL [https://cerc.co.uk/environmental-software/assets/data/doc\\_userguides/CERC\\_ADMS-Urban4.1.1\\_User\\_Guide.pdf](https://cerc.co.uk/environmental-software/assets/data/doc_userguides/CERC_ADMS-Urban4.1.1_User_Guide.pdf) (accessed 5.21.19)
- COMEAP 2018 Associations of long-term average concentrations of nitrogen dioxide with mortality [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/734799/COMEAP\\_NO2\\_Report.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/734799/COMEAP_NO2_Report.pdf). UK Department of Health Committee on the Medical Effects of Air Pollutants. PHE report no. 2018238
- Crouse D L et al 2015 Ambient PM<sub>2.5</sub>, O<sub>3</sub>, and NO<sub>2</sub> exposures and associations with mortality over 16 years of follow-up in the canadian census health and environment cohort (CanCHEC) *Environ. Health Perspect.* **123** 1180–6
- Cyrus J et al 2012 Variation of NO<sub>2</sub> and NO<sub>x</sub> concentrations between and within 36 European study areas: results from the ESCAPE study *Atmos. Environ.* **62** 374–90
- Ding J, van der A R J, Mijling B, Jalkanen J-P, Johansson L and Levelt P F 2018 Maritime NO<sub>x</sub> emissions over Chinese seas derived from satellite observations *Geophys. Res. Lett.* **45** 2031–7
- Faustini A, Rapp R and Forastiere F 2014 Nitrogen dioxide and mortality: review and meta-analysis of long-term studies *Eur Respir J.* **44** 744–53
- Fu M, Liu H, Jin X and He K 2017 National- to port-level inventories of shipping emissions in China *Environ. Res. Lett.* **12** 114024
- Fuller G 2018 *The Invisible Killer: The Rising Global Threat of Air Pollution—and How We Can Fight Back* (UK: Melville House)
- Fuller G W and Font A 2019 Keeping air pollution policies on track *Science* **365** 322–3
- GADM 2019 GADM [WWW Document]. GADM Maps Data. URL <https://gadm.org/> (accessed 10.10.19)
- Gao J et al 2015 The variation of chemical characteristics of PM<sub>2.5</sub> and PM<sub>10</sub> and formation causes during two haze pollution events in urban Beijing, China *Atmos. Environ.* **107** 1–8
- Guangzhou Municipal Public Security Bureau 2016 The number of deaths in Guangzhou traffic accidents has dropped for 13 consecutive years [WWW Document]. URL ([http://gzjd.gov.cn/gzjd/gaxw\\_ztbd\\_ctgc/201602/67b06e82303f4f1bb3e6f7225f187552.shtml](http://gzjd.gov.cn/gzjd/gaxw_ztbd_ctgc/201602/67b06e82303f4f1bb3e6f7225f187552.shtml)) (accessed 5.21.19)
- Guo H, Otjes R, Schlag P, Kiendler-Scharr A, Nenes A and Weber R J 2018 Effectiveness of ammonia reduction on control of fine particle nitrate *Atmospheric Chem. Phys.* **18** 12241–56
- Gurung A, Levy J I and Bell M L 2017 Modeling the intraurban variation in nitrogen dioxide in urban areas in Kathmandu Valley, Nepal *Environ. Res.* **155** 42–8
- He B, Heal M R and Reis S 2018 Land-use regression modelling of intra-urban air pollution variation in China: current status and future needs *Atmosphere* **9** 134
- He B, Heal M R, Humstad K H, Yan L, Zhang Q and Reis S 2019 A hybrid model approach for estimating health burden from NO<sub>2</sub> in megacities in China: a case study in Guangzhou *Environ. Res. Lett.* **14** 124019
- Huang J, Pan X, Guo X and Li G 2018 Health impact of China's air pollution prevention and control action plan: an analysis of national air quality monitoring and mortality data *Lancet Planet. Health* **2** e313–23
- Jerrett M, Arain A, Kanaroglou P, Beckerman B, Potoglou D, Sahuvaroglu T, Morrison J and Giovis C 2005 A review and evaluation of intraurban air pollution exposure models *J. Expo. Anal. Environ. Epidemiol.* **15** 185–204
- Kanakidou M 2019 China's nitrogen management *Nat. Geosci.* **12** 403–4
- Kostka G 2016 Command without control: the case of China's environmental target system *Regul. Gov.* **10** 58–74
- Li Y, Lin C, Lau A K H, Liao C, Zhang Y, Zeng W, Li C, Fung J C H and Tse T K T 2015 Assessing long-term trend of particulate matter pollution in the pearl river delta region using satellite remote sensing *Environ. Sci. Technol.* **49** 11670–8
- Liu F, Beirle S, Zhang Q, van der A R J, Zheng B, Tong D and He K 2017 NO<sub>x</sub> emission trends over Chinese cities estimated from OMI observations during 2005 to 2015 *Atmospheric Chem. Phys.* **17** 9261–75
- Liu T et al 2018 Long-term mortality benefits of air quality improvement during the twelfth five-year-plan period in 31 provincial capital cities of China *Atmos. Environ.* **173** 53–61
- Lucock M, Jones P, Veysey M and Beckett E 2017 B vitamins and pollution, an interesting, emerging, yet incomplete picture of folate and the exposome *Proc. Natl Acad. Sci.* **114** E3878–9
- MEIC 2016 Multi-resolution Emission Inventory (MEIC) [WWW Document]. URL <http://meicmodel.org/> (accessed 3.30.19)



- Ministry of Ecology and Environment 2012 Ambient air quality standards [WWW Document]. URL [http://bz.mee.gov.cn/bzwb/dqhjbh/dqhjbz/201203/t20120302\\_224165.shtml](http://bz.mee.gov.cn/bzwb/dqhjbh/dqhjbz/201203/t20120302_224165.shtml) (accessed 5.21.19)
- Ministry of Ecology and Environment of the People's Republic of China 2018 中华人民共和国大气污染防治法 (Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution) [WWW Document]. Minist. Ecol. Environ. Peoples Repub. China. URL [http://zfs.mee.gov.cn/fl/201811/t20181113\\_673567.shtml](http://zfs.mee.gov.cn/fl/201811/t20181113_673567.shtml) (accessed 11.3.19)
- Ou J, Yuan Z, Zheng J, Huang Z, Shao M, Li Z, Huang X, Guo H and Louie P K K 2016 Ambient ozone control in a photochemically active region: short-term despiking or long-term attainment? *Environ. Sci. Technol.* **50** 5720–8
- People's Government of Guangzhou Municipality 2017 广州市人民政府门户网站 - 广州市人民政府关于印发广州市环境空气质量达标规划(2016–2025年)的通知 [WWW Document]. Guangzhou Munic. Environ. Air Qual. Plan 2016–2025. URL <https://gz.gov.cn/gzgov/s2811/201712/57727a1d77354f5dbc22bb5831aa7d93.shtml> (accessed 5.14.19)
- Qiao X, Guo H, Tang Y, Wang P, Deng W, Zhao X, Hu J, Ying Q and Zhang H 2019 Local and regional contributions to fine particulate matter in the 18 cities of Sichuan Basin, southwestern China *Atmospheric Chem. Phys.* **19** 5791–803
- Reis S et al 2012 From acid rain to climate change *Science* **338** 1153–4
- Reis S, Liška T, Vieno M, Carnell E J, Beck R, Clemens T, Dragosits U, Tomlinson S J, Leaver D and Heal M R 2018 The influence of residential and workday population mobility on exposure to air pollution in the UK *Environ. Int.* **121** 803–13
- Shi C, Shi Q and Guo F 2019 Environmental slogans and action: The rhetoric of local government work reports in China *J. Clean. Prod.* **238** 117886
- Stevens E L, Rosser F, Forno E, Peden D and Celedón J C 2019 Can the effects of outdoor air pollution on asthma be mitigated? *J. Allergy Clin. Immunol.* **143** 2016–2018.e1
- UN Environment 2019 A review of 20 Years' Air Pollution Control in Beijing [WWW Document]. UNEP. URL <http://unenvironment.org/resources/report/review-20-years-air-pollution-control-beijing> accessed 8.30.19
- Vardoulakis S, Kettle R, Cosford P, Lincoln P, Holgate S, Grigg J, Kelly F and Pencheon D 2018 Local action on outdoor air pollution to improve public health *Int. J. Public Health* **63** 557–65
- Visscher A D 2013 *Air Dispersion Modeling: Foundations and Applications* (Hoboken, New Jersey: John Wiley & Sons, Inc.)
- Walton H, Dajnak D, Beevers S, Williams M, Watkiss P and Hunt A 2015 Understanding the health impacts of air pollution in London [WWW Document]. Lond. Kings Coll. Lond. Transp. Lond. Gt. Lond. Auth. URL [https://files.datapress.com/london/dataset/understanding-health-impacts-of-air-pollution-in-london-/2015-09-29T13:18:57/HIAinLondon\\_KingsReport\\_14072015\\_final.pdf](https://files.datapress.com/london/dataset/understanding-health-impacts-of-air-pollution-in-london-/2015-09-29T13:18:57/HIAinLondon_KingsReport_14072015_final.pdf) accessed 6.2.17
- WHO 2013 *Health risks of air pollution in Europe—HRAPIE project* World Health Organization. [http://euro.who.int/\\_\\_data/assets/pdf\\_file/0006/238956/Health-risks-of-air-pollution-in-Europe-HRAPIE-project-Recommendations-for-concentration-response-functions-for-costbenefit-analysis-of-particulate-matter-ozone-and-nitrogen-dioxide.pdf](http://euro.who.int/__data/assets/pdf_file/0006/238956/Health-risks-of-air-pollution-in-Europe-HRAPIE-project-Recommendations-for-concentration-response-functions-for-costbenefit-analysis-of-particulate-matter-ozone-and-nitrogen-dioxide.pdf) (accessed 9.20.16)
- WorldPop 2019 WorldPop :: Population [WWW Document]. URL <https://worldpop.org/project/categories?id=3> accessed 11.19.19
- Xue L, Wang T, Louie P K K, Luk C W Y, Blake D R and Xu Z 2014 Increasing external effects negate local efforts to control ozone air pollution: a case study of hong kong and implications for other chinese cities *Environ. Sci. Technol.* **48** 10769–75
- Yu M, Zhu Y, Lin C-J, Wang S, Xing J, Jang C, Huang, J, Huang J, Jin J and Yu L 2019 Effects of air pollution control measures on air quality improvement in Guangzhou, China *J. Environ. Manage.* **244** 127–37
- Zhang P et al 2011 Long-term exposure to ambient air pollution and mortality due to cardiovascular disease and cerebrovascular disease in Shenyang, China *PLoS One* **6** e20827
- Zhang B, Cao C, Gu J and Liu T 2016a A new environmental protection law, many old problems? Challenges to environmental governance in China *J. Environ. Law* **28** 325–35
- Zhang H, Wang S, Hao J, Wang X, Wang S, Chai F and Li M 2016b Air pollution and control action in Beijing *J. Clean. Prod., Preventing Smog Crises* **112** 1519–27
- Zhu Y et al 2018 Sources of particulate matter in China: insights from source apportionment studies published in 1987–2017 *Environ. Int.* **115** 343–57